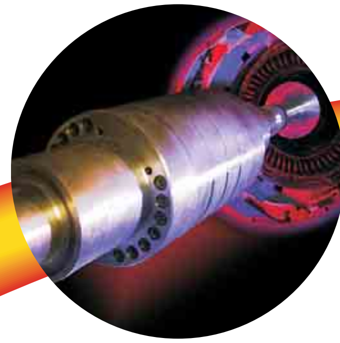
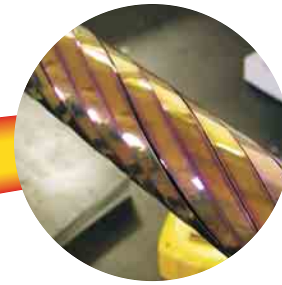
Selected

# High-Temperature Superconducting Electric Power Products





*Full-scale utility applications are moving onto the power system and …*

# Modernizing and Expanding the Electricity Infrastructure

**U.S. Department of Energy • Office of Electric Transmission and Distribution • Superconductivity Program for Electric Systems**

**May 2004**

# High Temperature Superconducting Power Products Capture the Attention of Utility Engineers and Planners

***Soon superconductors could be so common that we will drop the "super" and refer to them simply as conductors***

(Courtesy of American Superconductor Corp.)

*Flexible HTS conductors promise reduced operating costs and many other benefits when incorporated into electric power devices. They can change the way power is managed and consumed.*

## Critical Role of Wire

The application of superconductors to electric power systems has been pursued for more than 30 years. This persistence is starting to pay off and utilities that once politely acknowledged the long-term potential of superconducting applications are now paying close attention to several prototype devices that are being tested or are nearing testing on utility systems. What has prompted this interest is the development of electric wires that become superconducting when cooled to the affordable operating temperature realm of liquid nitrogen, as well as the development of coils, magnets, conductors, and machines and power components made with these wires. Superconducting wires have as much as 100 times the current carrying capacity as ordinary conductors.

## A Real Need

The timing is right for superconducting solutions to emerging business problems. Power generation and transmission equipment is aging and must be replaced. The 2002 National Transmission Grid Study made it clear that without dramatic improvements and upgrades over the next decade our nation's transmission system will fall short of the reliability standards our economy requires. With the introduction of deregulation, competition has intensified, and utilities are changing the way they evaluate capital investments. Environmental considerations too are increasing. Superconducting power products will help the industry meet these

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challenges by reducing operating costs, enhancing flexibility and reliability, and maximizing the capability of our existing infrastructure. Breakthroughs in advanced conductor materials and processing will enable superconducting transmission wires to carry three to five times the power of traditional wires through existing rights-of-way. This ultimately could be reflected in lower electricity rates for customers.

## Utility Uses

The following pages present technical profiles and specifications for five high-temperature superconducting (HTS) power products that are in the demonstration phase and are likely to gain a foothold in the marketplace. They are: transformers; current limiters; transmission cables; flywheels; and generators/large motors. These prototypes are providing the technical data and valuable operating experience base needed to accelerate the acceptance of superconducting technologies and to open up vast global markets.

## Modernizing the Infrastructure

The general acceptance of superconducting power equipment by the electric utilities and other end users will ultimately be based on the respective system performance, efficiency, reliability, and maintenance, operational lifetime, and installed and life-cycle costs compared to conventional technologies. High-temperature superconductivity can fundamentally reshape the technology of electricity delivery based on the results of full-scale demonstrations in key applications.

## U.S. Program

The U.S. Department of Energy (DOE) Office of Electric Transmission and Distribution (OETD) is the focal point for transmission and distribution policy and technology development activities within the Department of Energy. OETD supports national energy, economic, environmental, and educational interests by providing leadership in developing HTS electric power devices and facilitating their adoption by the utility industry and private sector. In the OETD Grid 2030 vision, superconductors will deliver large amounts of electricity over long distances into congested areas without the need for new transmission rights-of-way. The HTS prototype demonstrations described here are cost shared through the DOE Superconductivity Program's Superconductivity Partnerships with Industry (SPI), which is applying project readiness reviews to ensure the successful operation of these devices under real-world conditions.

### Department of Energy Superconductivity Program Goals

**Performance**

- Develop HTS wires with 100 times capacity of conventional copper/aluminum wires
- Design broad portfolio of electric equipment based on HTS
  - 50% size of conventional units with same rating
  - 50% reduction in energy losses compared to conventional equipment

**Cost**

- Wire cost $0.01/ampere-meter
- Equipment premium cost payback (efficiency savings) in 2-5 years of operation
- Equipment total cost payback during operating life

## *Superconductivity Partnerships with Industry*

From the beginning, industry has participated in the Superconductivity for Electric Systems Program through cooperative agreements, which draw on basic research conducted at the Department of Energy's national laboratories. These agreements lower the risk and cost to American industry of developing and demonstrating brand new HTS technology. The Superconductivity Partnerships with Industry are an integral part of the overall Superconductivity for Electric Systems Program. By fostering an integrated approach to solving technical problems, and by building strategic partnerships, SPI accelerates the deployment of HTS prototype devices and technologies for electric power and industrial applications. The cost-shared nature of the SPI program provides the vital funds needed to carry out pre-commercial activities designed to test HTS electrical devices and cables under actual working conditions. Competitions for new SPI projects are held every three to four years (for 3-4 year projects), which ensures that opportunities exist for new teams. Currently, DOE is a partner with industry in projects that focus on developing and testing first-of-a-kind products using HTS technology (Table 1).

### Table 1. Superconductivity Partnerships with Industry Goals

| Strategic Partnership Project (Electric Power Applications) | Major Goals |
|---|---|
| **Waukesha Transformer** | Develop and test a 5/10 MVA prototype HTS Transformer. Plan scale-up to 30/60 MVA HTS Transformers. |
| **SuperPower Fault Current Limiter** | Develop and test an HTS Matrix Fault Current Limiter, which will address transmission-level requirements of 138 kV. |
| **Niagara Mohawk Distribution Cable** | Develop and install a 350-meter, 48 MW HTS cable operating at distribution voltages (34.5 kV, 800 A) between 2 substations in Albany, NY. |
| **Southwire Distribution Cable** | Develop and operate several years a 27 MW, 100 foot, 3-phase HTS distribution cable supplying 3 factories. |
| **American Electric Power Triaxial Cable** | Develop and install a 3-phase, 200-meter, 69 MW, (13.2 kV, 3.0 kA) triaxial HTS cable at an American Electric Power (AEP) substation in Ohio. |
| **Long Island Power Authority (LIPA) Transmission Cable** | Develop and install a 3-phase, 610-meter, 600 MW HTS cable to operate at transmission voltages (138 kV, 2400 A) between 2 major substations on Long Island, NY. |
| **Boeing Flywheel Electricity Systems** | Develop a 10 kWh/3kW high efficiency FES using HTS bearings for power generation applications. Also, develop a 5kWh/100 kW FES for power quality applications with scale-up to 30 kWh. |
| **General Electric Generators** | Develop 1.5 MW and 100 MW HTS generators. |

# Transforming Transformers

**Use of HTS windings will turn power transformers into compact, environmentally friendly, and highly efficient performers that will help deliver high quality power cost effectively.**

HTS transformers use windings made of superconducting tape instead of conventional copper wire. The HTS tapes become superconducting at about 105 K. The tapes are usually cooled to liquid nitrogen temperatures (77 K, or -196°C) or lower to achieve best performance. At these temperatures the superconducting tapes allow current to be transported with nearly zero resistance. However, HTS transformers must still cope with eddy current and ac losses in the windings that require refrigeration power. These losses are small compared to losses due to resistive heating in conventional transformer windings. HTS transformers offer the possibility of operating with low losses and at 10 to 30 times greater current density than conventional transformers. The windings are electrically insulated with dielectric materials which are designed to meet ANSI standard dielectric tests for system voltages and the associated basic impulse insulation test levels.


(Courtesy of Waukesha Electric Systems)

## *System Advantages*

HTS transformers have potential advantages over conventional transformers in the following areas: about 30% reduction in total losses, about 45% lower weight, and about 20% reduction in total cost of ownership. These advantages are based on a 100 MVA transformer with HTS wire providing a critical current density of 10 kA/cm$^2$ and ac losses of 0.25 mW/A-m in a parallel field of 0.1 Tesla. Additional benefits include: unprecedented fault current limiting functionality which is expected to protect and reduce the cost of utility system components, and reduced operating impedance, which will improve network voltage regulation. In addition to greater efficiency than conventional transformers, HTS transformers eliminate oil-and-paper for electrical insulation and cooling, thus reducing fire and environmental hazards associated with oil-based systems. These benefits enable HTS transformers to have higher power densities so they can be sited in high-density urban areas and inside buildings.

## *Greater Effective Capacity*

Utility engineers envision the benefits of HTS transformers and how they could solve substation problems. A substation engineer at Energy East states, "HTS transformers are attractive...because they are much smaller, have greatly extended overload capability and don't have fire and environmental problems associated with insulating oil." A senior engineer at Energy East adds, "Our typical substation is designed with two transformers. If one transformer fails, the other is sized to carry the load of both during the emergency. An HTS transformer can carry up to 200 percent of nameplate rating indefinitely without loss of transformer life. This means we can buy transformers of lower rating to do the same job or pack up to four times the capacity onto the same footprint area. HTS is a breakthrough technology that promises to bring sweeping changes to transformers."

## Low Impedance—High Returns

Conventional transformers are designed with large impedances (typically 8%-10%). This can affect the voltage regulation and reactive power demand in the system. HTS transformers can be designed to have an impedance of about 25% of a conventional transformer. With fault current limiting features, an HTS transformer can manage fault currents to much lower levels. Examples of financial benefits due to the enhancements provided to power system performance and operation are shown in Table 2.

## Demonstrating Performance

DOE is currently co-funding a project with Waukesha Electric Systems to develop and demonstrate a 5/10 MVA, 26.4/4.16 kV, HTS transformer at Waukesha's manufacturing plant in Wisconsin. A 1 MVA single-phase transformer has already been demonstrated by Waukesha. It consists of a test bed with a core cross-section of a 30-MVA transformer with a 138 kV/13.8 kV rating. The HTS winding is operated at 25-30 K and the core is at near room temperature. A prototype of the 5/10 MVA has been completed and preliminary testing is in progress. As the costs of producing superconducting wire continue to fall, plans call for the construction of a 30/60-MVA HTS transformer incorporating second-generation HTS wire by 2008. Tables 3 and 4 illustrate the

**Table 2. Examples of Potential Financial Benefits. (The numbers provided are typical industry averages)**

| HTS Transformer Characteristic | Financial Benefits |
|---|---|
| **Current Limiting Capacity** | |
| • Use conventional breaker instead of high current $SF_6$ breaker | $25,000 each |
| • Replace EHV breaker with circuit switcher | $25,000 each |
| • Use load break switches instead of breakers | $ 6,000 each |
| • Elimination of current limiting reactors | $20,000 each |
| **Reduced Impedance(*): Impact on Power System** | |
| • Reduced need for Load Tap Changer units (voltage regulation) | $75,000 per LTC |
| • Reduced system VAR requirements (Static VAR Compensation) | $50,000 per MVAR |
| • Reduction in capacitor banks (reduced reactive power losses) | $13,000 per 10 MVA |
| **Reduced Transformer Impedance (*): Impact on Generation** | |
| • Reduced VAR requirements freed up for system, at $50/kVAR | $2.5 million |
| Additional available generator capacity from improved operation: **25 MW** | |
| 1. Avoided capital cost, at $300/MW for gas turbine generator | $7.5 million |
| 2. Additional revenue, at $0.04/kWh, 50% capacity factor | $4.4 million (annual) |

(*) Assumed: HTS transformer impedance is 25% of that of conventional transformer

(ABB Power T&D Company, 1998)

increasing performance, complexity, and capacity of HTS transformers.

In a previous project, ABB installed a three-phase 630 kVA, 18.7 kV/420 V HTS transformer at an electric utility in Geneva,

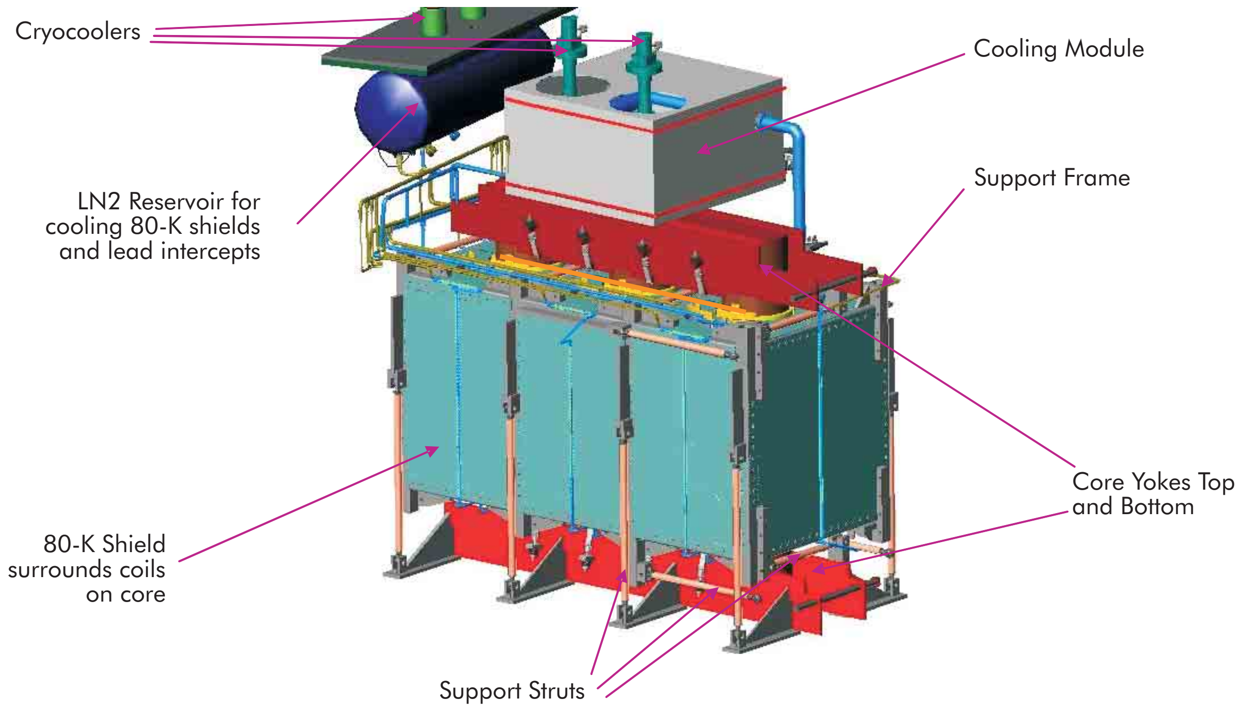
### Table 3. Specifications for the 1-MVA, 5/10-MVA, and 30/60-MVA Transformers show a progression in performance and complexity.

| | 1-MVA | 5/10-MVA | 30-MVA |
|---|---|---|---|
| Connection | 1-Phase | 3-Phase, D/Y | 3-Phase, D/Y |
| Pri/Sec Voltage | 13.8 kV/6.9 kV | 24.9 kV / 4.2 kV | 138 kV / 13.8 kV |
| Pri/Sec BIL | N/A | 150 kV / 50 kV | 550 kV / 110 kV |
| Pri/Sec Coil Current | 72.5 A / 145 A | 67 A / 694 A | 72 A / 1255 A |
| Overload Ratings | N/A | 2-sec 10X, 48-hr 2X | 2-sec 10X, 48-hr 2X |
| 3-Day Power Outage Handling | N/A | Backup Motor/ Generator | Backup Motor/ Generator |
| Cooling System | Cryocooler | Cryocoolers | Cryocoolers |
| Instrumentation | Local | Local | Remote |

### Table 4. HTS Transformer Milestones

| | Voltage | Capacity |
|---|---|---|
| Current Status | 13.8 kV | 1.7 MVA |
| 2004 | 24.9 kV | 10 MVA |
| 2007 | 138 kV | 50 MVA |
| 2010 | 345 kV | 340 MVA |

## Major Components of 5/10-MVA Transformer Design




(Waukesha Electric Systems)

Switzerland. This unit was successfully serviced and tested for one year during the late nineteen nineties and was then decommissioned.

## *Partners*

Waukesha Electric Systems, SuperPower, Energy East, Oak Ridge National Laboratory.

# Surge Protection for Power Grids

***HTS current limiters will provide utilities with surge protection within their local power transmission and distribution systems. They will prove to be economical and efficient fault current limiters.***

## Old Problem

Every lightning strike, short circuit and power fluctuation is a potential catastrophe for power companies and their customers. These common events cause fault currents, which are sudden, momentary surges of excess energy or current that can damage and destroy expensive transmission and distribution equipment – and cut off service throughout a utility's grid.

## New Solution

Utilities overwhelmingly indicate a critical need for a highly efficient current limiter. Yet few are satisfied with conventional solutions, which include larger, more costly transformers, inefficient current-limiting reactors, multiple circuit breaker upgrades, and substation upgrades. HTS current limiters are far more capable than conventional solutions in several critical ways. They are reusable, require minimal maintenance, and do not need replacement after being activated. Most importantly, they also allow utilities to increase line power capacity and make more effective use of the grid.

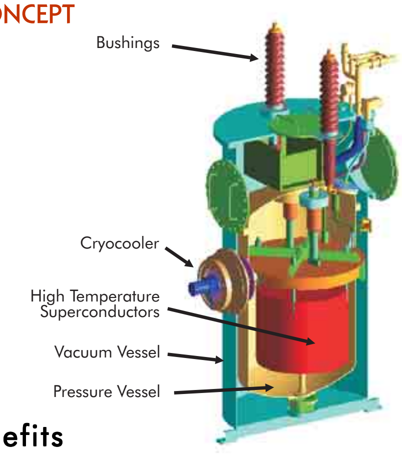
Superconductors are natural fault current limiters because of their ability to change rapidly from a superconducting, zero impedance state to a normal high impedance state in a fault situation.

During normal operation, an HTS current limiter is invisible to the grid without any losses or impact on system transient stability. When a fault occurs an HTS current limiter can detect a power surge and redirect it to a coil that can safely absorb the surge. This device limits the impact of a fault current, ensuring that the rating of existing protection equipment is not exceeded and can isolate the fault from the rest of the system. HTS fault current limiters are compatible with existing protection devices. Their maximum allowable current is adjustable, which means greater system flexibility, and they can defer the need for more costly transmission and distribution system upgrades.

## Matrix Fault Current Limiter

Work is underway on a Matrix Fault Current Limiter (MFCL), which will address transmission level requirements (138 kV). The MFCL will be

### Low Voltage Pre-Prototype MFCL Concept




**Benefits**

- Fast response to fault currents without active controls or power electronics (low cost)
- Avoids expensive multiple circuit breaker upgrades
- Environmentally benign

(SuperPower)

### Table 5. 138 kV MFCL Milestones

| | |
|---|---|
| Current Status | Conceptual design completed |
| 2004 | Scaled pre-prototype demo |
| 2005 | Alpha prototype demo |
| 2006 | Beta prototype field test demo |
| 2007 | First commercial units |

based on proprietary technology developed by SuperPower, and will combine intrinsic HTS properties and conventional copper coil technology to achieve current limiting. The MFCL will utilize BSCCO 2212 elements in the form of tubes manufactured by Nexans SuperConductors using their proprietary Melt Cast Processing technique. The combination of SuperPower's and Nexans' technologies results in a design that is low cost and highly modular and scalable. Under fault conditions the superconducting tubes will transition to a resistive state, thereby redirecting the fault current to coils that provide a current limiting impedance into the grid. The modular matrix approach provides the ability to add redundant elements in order to increase reliability. The MFCL development program utilizes a Technical Advisory Board consisting of utility members that provide guidance on expected application requirements. This includes considerations such as a minimum of 30 year lifetime with minimal maintenance. Clark Gellings, vice president of power delivery and markets for the Electric Power Research Institute (EPRI) said, "Superconductivity is an

| MFCL Features |
|---|
| • Modular matrix design is scaleable<br>• Invisible during normal operation<br>• Passive detection and insertion of current-limiting impedance without active monitoring or controls<br>• Reliable with built-in redundancy in matrix configuration<br>• Low cost (uses off-the-shelf components)<br>• No hazardous oil |

*The superconducting current controller was delivered to the Southern California Edison Center Substation for testing. (General Atomics)*

important technology for the 21st century. Superconducting fault current limiters have the potential to improve system performance, reliability, and safety in this era of increasing power demands and complex interactions, which would be of substantial benefit to EPRI's members." Table 5 shows the anticipated progress of the 138 kV MFCL.

## *Early Prototype Exceeds Design Goals*

Beginning in 1993, DOE teamed with General Atomics in a Phase 1 SPI project to develop a 2.4 kV HTS device capable of controlling fault currents up to 3 kA. In early tests, the prototype controller successfully reduced a 3.03 kA fault current, performing 37% above specifications. The specifications also called for the current controller to be able to handle 2 faults of 400 milliseconds (ms) each, spaced 15 seconds apart. The prototype limited these fault currents within an interval of less than one second. The 2.4 kV current controller was successfully tested in September 1995 at a Southern California Edison (SCE) substation.

This was soon followed by a Phase 2 SPI project in which a 15 kV controller was developed (Table 6). The prototype 15 kV device was actually rated at 17 kV, 45 kA, and 765 MVA. It operated at 40 K and experienced a peak magnetic field in normal operation of 0.3 Tesla and peak magnetic field in fault conditions of 1.4 Tesla. While the coil's normal operating current is 2,000 A dc, it is able to handle 9,000 A rms during the fault condition. In 1999, the 15 kV fault current controller was shipped to Southern California Edison where it was tested under high voltages. Failure of an auxiliary piece of equipment rendered one phase inoperable, however, single-phase testing continued, and the controller achieved fault reduction and subcycle fast breaker operation at 12.47 kV and 10 kA. This system was returned to Los Alamos National Laboratory where it was refurbished and successfully tested again in 2002.

## Partners

Matrix Fault Current Limiter
SuperPower Inc.,
Nexans SuperConductors GmbH, EPRI, Argonne National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory.

### Table 6. 15 kV Fault Current Limited Device Design

| Parameter | Specification |
|---|---|
| Maximum operating voltage | 17 kV rms |
| Normal operating current | 1,200 Amps rms |
| Maximum interceptable current | 45 kA (asm) |
| Breakdown insulation level | 110 kV |
| Maximum ambient temperature | 323 K |
| Designed fault reduction | 80% |
| Fast breaker operation | 8 ms |
| Multiple fault limiting | Two faults, 1s each 15 s apart |

# High-Capacity Transmission Cables

***HTS cables cooled to 77 K are being demonstrated and will soon be carrying at least 3 to 5 times more power than conventional cables through the existing underground city pipes. This offers strategic benefits to utilities and a cost-effective means for repowering the existing electricity delivery infrastructure.***

## *New Possibilities*

Network designers have traditionally increased voltage to transmit more power efficiently. For a given capacity line, higher voltage results in lower current and lower ohmic ($I^2R$) heating losses. This has entailed large investments in high-voltage transformers and related equipment, as well as large electric losses. HTS cables may make it possible to lay out grids in innovative ways to position generators closer to customers, without having to step voltage up and down as frequently as is done today. The economic savings would be significant.

## *Growing with the Grid*

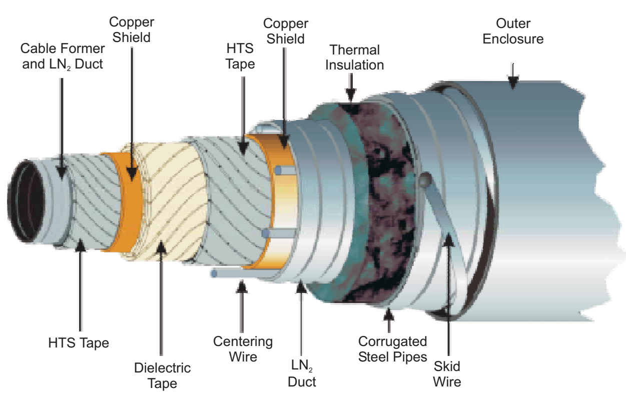
Presently, about one quarter of the 2,200 miles of underground transmission cables in the U.S. have been in place beyond their rated lifetimes. HTS cables can meet increasing power demands in urban areas via retrofit applications using existing cable conduits and can eliminate the need to acquire new rights-of-way. Presently, two to three underground copper cables are needed to achieve the capacity of one overhead transmission line, and installation costs are 20 to 30 times higher.

In HTS power transmission cables, conventional conductor wire of copper or aluminum is replaced by HTS wire, enabling the cable to carry greater amounts of current with lower resistive losses. Successful application of HTS conductors to transmission cables would allow the use of underground HTS cables for the replacement of overhead lines. Significant environmental benefits are obtained from the use of liquid nitrogen coolant rather than oil.

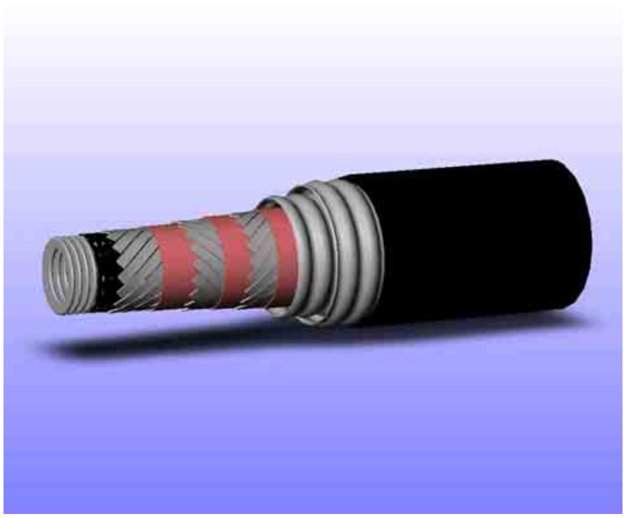
## *Advances in Cable Design*

Southwire Company has developed a "cryogenic dielectric" design which exposes the cable's electrical insulation to liquid nitrogen temperatures. This design offers the added benefit of an HTS shield layer, which lowers ac losses and eliminates the external electromagnetic field. In this design, a central former is concentrically surrounded with HTS tape, electrical insulation, and another layer of HTS tape. The entire assembly is then insulated and jacketed to protect it from thermal and physical damage. The cable is cooled by passing liquid nitrogen through the hollow central former along the length of the cable, which is then returned, through gaps in an outer layer of the cable assembly.

The Southwire project resulted in a 30-m, three-phase, 12.5 kV, 1.25 kA power cable, which is




*Cryogenic Dielectric Cable Design. (Southwire)*



Tri-axial Superconducting Cable. (Southwire)

now installed in Carrollton, Georgia. The cable has been running continuously since February 2000, providing power to two of Southwire's own manufacturing plants and its corporate headquarters.

To further reduce costs and ac losses in the three-phase power line, Southwire has been investigating a new "tri-axial" design for its power cable. In this scheme, rather than having three independent HTS cables comprising the three phases, a single cable is constructed with three electrically insulated layers of superconductor built around the same axis. Southwire believes the new design will reduce the cooling load of the system, and less superconducting tape will be required. Having concentric phases will also lead to reduced electric and magnetic fields. Southwire and Oak Ridge National Laboratory have undertaken extensive testing on the tri-axial cable design, using a 5-meter, 1.3 kA prototype for bend and termination design and testing.

Three-phase cable inserted into cryostat. (Courtesy of Oak Ridge National Laboratory)

## Ultera 3-Phase HTS Cable Project

Ultera, a joint venture between Soutwire and nkt cables, is now developing a 200-m, three-phase HTS power cable for installation at American Electric Power's Bixby substation in Columbus, Ohio. The new cable will be six times as long as that installed in Carrollton, and will carry about two and a half times as much power. This 13.2 kV, 3.0 kA (69 MW) tri-axial cable system is intended to demonstrate the feasibility of an underground HTS cable installation. This cable will have the highest continuous duty current rating of the three SPI projects now in development. Lessons learned during the Carrollton tests are being applied to the development of a simplified and reliable cryogenic system that will not be affected by multiple ninety-degree bends in the underground conduit. Cables, terminations, and other components are being fully tested in the laboratory prior to the line being installed and energized in 2006.

## Albany Cable Project

SuperPower, along with cable manufacturer Sumitomo Electric Industries and The BOC Group, will be developing and installing a 350-meter underground cable between two substations in the Albany, New York distribution system operated by Niagara Mohawk. The 34.5 kV, 48 MW, 800 ampere cable will be the first installation in a live grid at distribution voltages and will include a cable-to-cable splice 30 meters from one end. The splice will also be a first of its kind and is viewed as a critical demonstration of additional technology necessary to install and operate longer length HTS cables for full commercial applications.

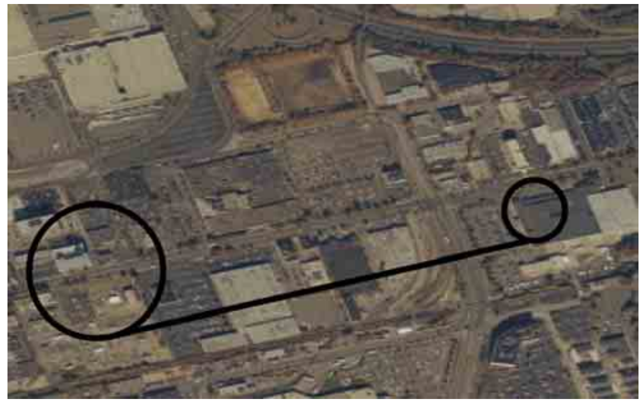
## Albany Cable Project


Demonstration of a 350-m underground HTS distribution cable and cable-to-cable joint in Niagara Mohawk's grid. (Niagara Mohawk)

During the latter stages of the project, the 30-meter cable section will be replaced with an identical length using second generation HTS wire technology manufactured by SuperPower. This will be the first in-grid demonstration of a second generation coated conductor anywhere in the world. The first stage of the project is expected to be completed and operating in 2006, with the second phase – adding the second generation conductor – completed in 2007.

Distinctive features of the Albany HTS cable will be 3-phases in a single cryostat and a copper core cable design similar to this previously demonstrated 66 kV HTS cable. (Sumitomo Electric Industries)

## Long Island Cable Project



*The 610-meter, 138 kV/600MW cable will be the first commercial application of HTS cable at transmission voltages. (LIPA)*

## *Long Island Cable Project*

American Superconductor (AMSC) and cable manufacturer Nexans are working to develop and install a 138 kV, 2400 A, 3-phase superconducting cable between two major substations of the Long Island Power Authority (LIPA). The nearly half-mile power cable system will be the world's first installation of a superconducting cable in a live grid at transmission voltages. The 2,000-foot transmission circuit will be located underground in an existing right of way in East Garden City, Long Island. With a capacity of 600 MW, the cable system will be an integral part of the LIPA grid and is expected to be installed and operating by the end of 2006.

The cable will be assembled by Nexans using HTS wire manufactured by AMSC. Air Liquide will provide refrigeration equipment and oversee operation of the cryogenic cooling system for the cable. "Siting new transmission lines has become a formidable challenge in congested areas such as Long Island," said Michael Hervey, director of Transmission and Distribution for LIPA. "Superconductor cables can transmit substantially more power than conventional cables in the same right of way,

## TABLE 7. HTS POWER CABLE MILESTONES

| | Voltage | Capacity | Length |
|---|---|---|---|
| Current Status | 12.5 kV | 25 MW | 30 meters operating since 2000 (Southwire) |
| 2005 | 13.2 kV | 69 MW | 200 meters |
| 2006 | 34.5 kV | 48 MW | 0.2 miles |
| 2007 | 138 kV | 600 MW | 0.5 miles |
| 2008 | 138 kV | 600 MW | >2 miles |
| 2010 | 230 kV | 1,000 MW | multiple 10-mile links |

which will help us to continue meeting our customers' growing demands for electricity."

## Partners

*Southwire 3-Phase HTS Cable Project*
Ultera (Southwire and nkt cables), American Electric Power, Oak Ridge National Laboratory.

*Albany Cable Project*
SuperPower, Niagara Mohawk, Sumitomo Electric Industries, The BOC Group, NYSERDA.

*Long Island Cable Project*
American Superconductor, Nexans, Long Island Power Authority, Air Liquide.

## First Urban Cable Retrofit

In 2001, DOE and Pirelli Cable co-funded a project to develop and manufacture a 120-m, 24 kV, three-phase HTS cable prototype and test it using conventional, industry-accepted techniques.

The 2,400 A, single conductor cable was installed in Detroit Edison's Frisbie substation. It used only 250 pounds of superconducting wire (provided by American Superconductor) to conduct as much power as the 18,000 pounds of copper it replaced. The cable employed a warm dielectric design, in which the electrical insulation is outside the thermal insulation and is not exposed to liquid nitrogen temperatures. The cable was cooled by pressurized liquid nitrogen circulating in a hollow core.

Although the superconducting wire was not damaged during installation, the presence of right angle bends in the underground conduit caused a number of welds on the cryostat's vacuum system to fail. As a result, two of the HTS phases were replaced with conventional cable, and testing continued on the remaining superconducting phase until 2003.


(Courtesy of Pirelli)

The experience gained from the Detroit Edison demonstration project shows the importance of testing HTS cables in the harsh utility environment under which superconducting cable and refrigeration equipment will have to operate for many years. Rigorous testing of cryogenic and other components is leading to improvements intended to boost performance and durability, while SPI Project Readiness Reviews are maximizing the chances for project success.

# Flywheel Energy Storage – An Alternative to Batteries

***Flywheels based on frictionless superconducting bearings will improve power quality and reliability.***

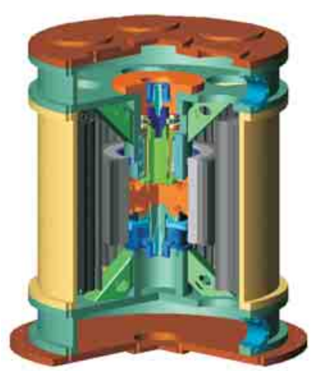
Flywheel electricity systems can be applied to increase electric utility efficiency and reliability in two areas – electric load leveling and uninterruptible power systems (UPS) applications. As an energy storage device, flywheel systems can transform electric energy into kinetic energy via an electric motor, store the energy in the rotation of the flywheel, and use the rotational kinetic energy to regenerate electricity as needed.

Electric utilities and some industries use flywheels to ensure that the supply of electric power to their customers and equipment is not interrupted by unforeseen disturbances of the power grid. Flywheels can therefore eliminate both momentary voltage and frequency fluctuations and longer-term interruptions of power. They can also allow power plants to operate more efficiently by smoothing the fluctuations caused by load following. Compared to chemical storage batteries, a flywheel system should be able to hold more energy in reserve in a smaller, more environmentally friendly package, and last far longer.

## *Increased Flexibility – Reduced Waste*

Flywheel electricity systems have the potential to provide increased system flexibility and efficiency through load leveling, maximizing system potential, and reducing electricity waste. Traditional flywheel designs have been prohibitive in all but the most specific applications, because of friction and complex control systems resulting in energy losses of at least 3 to 5% per hour. The less friction in the wheel bearings and the less air resistance on the flywheel, the more efficient its energy storage capability. Until the recent development of bulk superconducting, self-centering HTS bearings, the energy loss associated with both mechanical and electromechanical bearings has been prohibitively high. Actively controlled electromagnetic bearings reduce this problem due to their non-contact nature. However, these systems face significant problems including scaling to utility sizes, high costs associated with complex control systems, and standby energy losses. With the development of efficient bearings based on high-temperature superconductors, losses can be reduced to less than 0.1% per hour while maintaining a stable bearing for the rotating wheel. Compared to traditional rolling contact or conventional electromagnetic bearings, HTS bearings will provide dramatically reduced frictional and

### 5 kWh / 100 kW UPS Demo System



(Boeing)

parasitic load losses. Energy losses of less than 0.1% per hour have already been demonstrated.

Argonne National Laboratory has teamed with Boeing Phantom Works to develop the technology for a large flywheel system containing superconducting bearings. The UPS applications of the flywheel electricity system have the potential to save both utilities and consumers millions of dollars in time and work losses.

Boeing and the Department of Energy collaborated on two earlier projects that led to the development of a 2 kWh laboratory flywheel system and a 10 kWh/3 kW load-leveling flywheel system. Lessons learned from experiments with various rotor designs of the 3-kW flywheel are helping to build the technology base needed for a 5 kWh/100 kW system that will soon be demonstrated for Southern California Edison. Table 8 shows the specifications for the 5 kWh/100 kW system. Boeing hopes to develop and perform in-service testing on an ambitious 30 kWh flywheel system at SCE by 2006.

## Partners

Boeing, Argonne National Laboratory, Southern California Edison

### Installing the 100 kW Flywheel Rotor Assembly

(Courtesy of Boeing)

### Table 8. 5 kWh/100 kW UPS Flywheel Specifications

| Design | Type |
|---|---|
| HTS Bearing | 4 radial poles with horizontal magnet polarity |
| Cryogenic Support | Cryomech GM Cooler |
| Lift Bearing | Push-pull (3 rings) |
| Rim and Hub | Thin rim (ri = 0.59 ro) and aluminum hub |
| Rotordynamics | Ip/It > 1.15<br>No modes in entire range |
| Motor/Generator | 6-pole PM machine, large radial gap |
| Power Electronics | Motor control and inverter with utility interface to 480 VAC |

# Unleashing HTS Horsepower – Generators and Motors

***Big outputs come in small packages due to revolutionary generators and electric motors that use HTS technology to maximize performance while reducing size, weight and energy costs.***

| GE HTS Generator Characteristics |
|---|
| • Easier HTS field coil design<br>• HTS rotor same size as conventional rotor<br>• Common technology for new and retrofit units |

A generator converts rotational mechanical energy, such as that from a steam or gas turbine, into electricity. It does this by rotating a magnetic field to produce voltage in stationary armature conductors. The magnetic field can be produced with copper windings or permanent magnets. In large machines, mechanical considerations and the desire to vary the level of field produced typically favor the use of copper windings over permanent magnets. Large generators are typically installed at power generation plants. HTS generators have the potential to improve efficiency in new power plants as well as through the retrofitting of existing plants.

## *Immediate Benefits*

The major benefit of the adaptation of HTS generators into power plants is increased system efficiency. Generators lose power in the rotor windings and the armature bars. By using superconducting wire for the field windings, the losses in the rotor can be practically eliminated. Other losses can also be reduced because of increases in power density and the reduction in the required cooling capacity. HTS generators will produce electric power with lower losses than their conventional equivalents. Even small efficiency improvements can produce big dollar savings. A half of one percent improvement in generation efficiency provides a utility or independent power producer with additional capacity to sell with a related value of nearly $200,000 per 100 MW generator, assuming electricity prices of 5 cents/kWh and 8,000 operating hours per year.

Generator designers follow two distinctly different approaches to the design of an HTS generator. One approach, followed by GE, retains the conventional stator core and frame with its magnetic structures and adds an HTS rotor that contains an iron core. This approach completely eliminates any risk associated with the design of the stator and provides a magnetic structure in the rotor to enhance torque transmission. It offers immediate efficiency benefits, compatibility with the turbine drive train, and the ability to retrofit HTS rotors into existing generators.

As an alternative, one can use an "air core" design, eliminating much of the structural and magnetic steel thus obtaining a generator that can be smaller and lighter than an equivalent conventional generator. In applications where size or weight reduction is an advantage (although not utility power plants), such as ships

| HTS Generator Major Customer Benefits |
|---|
| • 0.35-0.55% efficiency gain (reduced emissions and fuel)<br>• Increased T&D stability (VAR capability, SCR)<br>• Generator uprate capability |

### Table 9. HTS Generator Milestones

| | Voltage | Power Rating |
|---|---|---|
| 2003 | 4.16 kV | Tested 1.8 MW demo (GE) |
| 2006 | 13.8 kV | 100 MW |
| 2012 | 18-20 kV | 350 MW |

or locomotives, superconducting generators could increase generating capacity without using additional space. Construction, shipping, and installation may be simplified and perhaps less costly as a result of the smaller dimensions and lighter weight. However, air core HTS generators do pose significant reliability risks in regard to transmission of torque within the generator and the potential for amplification of fault torques on the turbine-generator drive train.

Another benefit of HTS generators can be lower generator reactances. This benefit can impact utility transmission and distribution stability considerations. One implication is a reduction in the amount of spinning reserve (unused but rotating generating capacity) needed to ensure a stable overall power system. Another benefit is that an HTS generator can be built to be significantly overexcited more easily than can a conventional generator, permitting power factor correction without adding synchronous reactors or capacitors to the power system. This improved system stability could result in improvements in reliability.

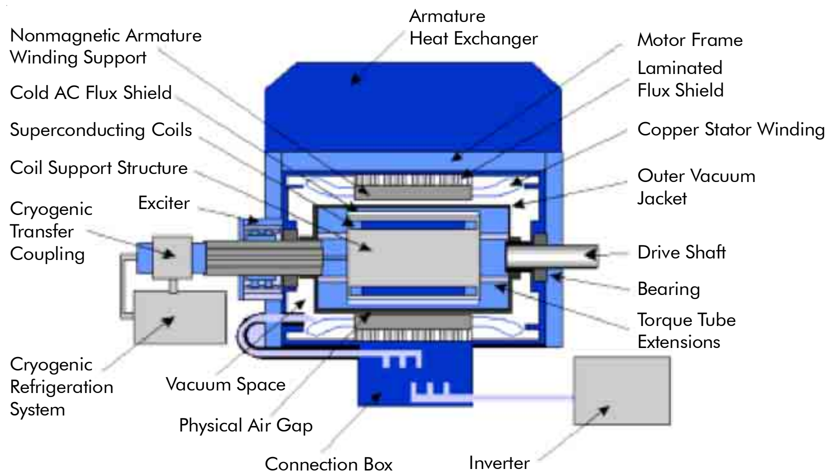
## Gearing for the Future

Generators represent a large, established worldwide market. The U.S. Energy Information Administration estimates that demand for new generation in the USA between today and 2025 will be 428 gigawatts (GW), or over 4,000 units the size of the generator that will result from this project. Additionally, hundreds of gigawatts of existing generators will face replacement in the next two decades. The worldwide market is expected to be even larger. Forecasters predict electricity demand to nearly double by the year 2020, with new generation facilities coming on-line in virtually every corner of the globe. GE and DOE originally formed a partnership to investigate HTS generators in 1993, and sample generator windings were produced. The current HTS generator project began in mid-2002. Initial efforts focused on building and testing a 1.5 MW demonstration machine, and a rotor for this device has been constructed and tested. Following the laboratory testing of the 1.5 MW unit, the team began design of an HTS rotor for a full scale, 100 MVA generator. The 100 MVA rotor will be installed in a conventional generator and tested in the GE factory. GE expects the HTS generator to achieve a 0.35 to 0.55 percent efficiency gain over a copper winding generator.

### Rotor assembly for the 1.5 MW HTS generator prototype (GE Global Research Center)

(Courtesy of General Electric)

The GE project will utilize knowledge gained from earlier superconducting generator projects, but will differ in several important ways. GE will use the same stator core and armature winding. The frame, as well, will not be altered, so that the unit's geometry is compatible with turbines and other power plant equipment for retrofit applications. However, the new project will involve a new cryogenic refrigeration system, cryogenic transfer coupling, and rotor coil and support scheme. The unit will have a rotor diameter of up to a meter, and at that size the support structure must be able to withstand centripetal forces on the surface of the rotor of up to 10,000 g. GE has also stressed demonstrating HTS generator technology that will meet or exceed the established generator industry performance of 99 percent availability. Table 9 illustrates the great advances expected in HTS generator technology.



*HTS Motor: Design Features (Reliance Electric)*

## Electric Motors

Electric motors run the industrialized world. They also run huge power bills — $55 billion a year in the U.S. alone. Industrial motors of more than 1,000 hp consume about 20% of all electric power generated in the U.S. As industry looks for ways to cut expenses, one of the most promising solutions lies in the HTS motor.

## Immediate Savings

Industrial electric motors consume 70% of the electricity used in a typical manufacturing operation, so increased efficiency yields immediate savings in power costs. Each one percent in efficiency improvement provided by HTS motors would result in an estimated savings (across all motors of over 1,000 hp) of more than $300 million per year in the U.S. Over the lifetime of the HTS motor, the savings in power costs would exceed its capital cost. Reduced size and weight additionally cut costs associated with shipping, manufacturing, installing, and maintaining motors. More efficient operation also conserves non-renewable resources and generates fewer pollutants and greenhouse gases. Table 10 shows the anticipated progress in HTS motor development.

### Table 10. HTS Motor Milestones

| | Voltage | Power Rating |
|---|---|---|
| Current Status | 4 kV | 0.75 MW tested in 2001 (Reliance) |
| 2007 | 4 kV | 5 MW |
| 2010 | 10 kV | 5 MW |

## Basic Design

HTS motors can replace large motors (> 1,000 hp) for pump and fan drives in utility and industrial markets. Higher magnetic fields are produced with HTS windings with no rotor losses and significantly reduced energy losses in the armature. The use of HTS windings eliminates the need for iron teeth in the armature, which in turn leaves room for more armature copper. This increases motor rating, improving machine efficiency and lowering operating costs even further.

DOE and Reliance Electric, a division of the Rockwell Automation Company, cooperated to develop a cryogenically cooled, ultra-efficient synchronous motor with HTS field windings (Table 11). American Superconductor furnished the first generation HTS tape used to make the windings, and the 1,000-hp motor was demonstrated in 2001. Dave Paratore, President and Chief Operating Officer of American Superconductor said, "HTS motors and generators will provide significant value to industrial and utility companies alike through savings in acquisition and operating costs…HTS motors and generators can be less than half the size and weight of conventional machines, are less costly to manufacture, and are more efficient, especially in part-load applications." American Superconductor has also developed and tested a 5,000-hp industrial motor of its own design while Reliance plans to complete their 5,000-hp motor when the cost of second generation HTS wire reaches commercial levels.

## Partners

*100 MW Generator*

General Electric, American Superconductor, American Electric Power, Los Alamos National Laboratory, Oak Ridge National Laboratory

### Table 11. HTS Motor Specifications Coil Assembly Design

| Parameter | Value for 1,000 hp Motor | Value for 5,000 hp Motor |
|---|---|---|
| Output power (hp)/(kW) | 1,000/746 | 5,000/3,730 |
| Shaft speed (rpm) | 1,800 | 1,800 |
| Output torque (ft-lb)/(N-m) | 2,918/3,956 | 14,589/19,780 |
| Number of poles | 4 | 4 |
| Armature voltage (V) | 4,160 | 4,160 |
| Power factor | 1.0 | 1.0 |
| Predicted efficiency (% wo/ref) | 97.9 | 98.8 |
| Predicted efficiency (% w/ref) | 97.1 | 98.6 |
| Operating field current (Amps) | 126 | 152 |
| Operating field temperature (K) | 33 | 33 |
| Current density, Jc (kA/cm2) | 13.5 | 13.5 |
| Maximum field magnetic flux (T) | 1.5 | 1.85 |
| kA-turns/pole | 172 | 327 |
| Rotor outer diameter (in)/(cm) | 15.8/40.1 | 24/60.7 |
| Armature outer diameter (in)/(cm) | 27/68.6 | 38/96.5 |
| Armature length (in)/(cm) | 48/121.9 | 50/127 |

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